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ABSTRACT

This paper reviews the aspects of cognitive science that relate best to using electrical and magnetic recording to understand the function of brain systems. It outlines a framework for relating cognitive activities of daily life (typing, reading) to underlying neural systems. The framework uses five levels of analysis: task, elementary operations, components facilitation and inhibition, neural systems, and cellular level. Evidence is outlined which supports the idea that component facilitations and inhibitions in performance can be systematically linked to the activity of neural populations. The evidence is in the area of spatial attention and uses results of normal and brain injured subjects as well as data from surface electroencephalography and recording of single cells during selective attention tasks. (Author)

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A FRAMEWORK FOR RELATING COGNITIVE

TO NEURAL SYSTEMS

Michoel I. Posner

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A Framework for Relating Cognitive to Neural Systems[1]

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Introduction

The goal of this paper is to review the aspects of cognitive science that appear to relate best to efforts to use electrical and magnetic recording to understand the function of brain systems. To meet this goal it is important to understand the changes that have taken place in recent years, both in our understanding of brain function and in our understanding of cognition. It is on the latter changes that I plan to concentrate in this paper.

The term cognitive science relates to efforts by students of psychology, linguistics and artificial intelligence, among others, to produce a fundamental analysis of natural and artificial intelligence. This area is of enormous breadth and there would be no possibility of a thorough review here. Instead I first attempt to develop a framework which describes work in cognition at several levels of analysis most appropriate for the goal of developing a relation to underlying neural systems. I then then analyze recent work on spatial attention in more detail as a model use of the framework to guide integrative research.

Framework

Figure 1 provides an overall framework of five levels that

Insert Figure 1 about here

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seem to me to provide a basis for establishing empirical relationships between complex cognitive activity and brain systems. In the history of research on localization of function from the time of phrenology to the present there has been greatly oversimplified conceptions of cognition. Phrenology sought to localize very general mental faculties or cognitive traits that might underly the ability to compose music, play chess or perform some other complex skill. Following the development of behaviorism, the study of cognition was often confined to what could be observed in overt behavior, or with the aid of a very few simple internal constructs, mostly motivational, that tied internal systems to overt behavior. This approach still dominates in the study of behavioral neuroscience.

In the last twenty years, complex cognitive tasks such as playing chess, reading, or manipulating visual images, have been subjected to detailed analysis. In his study of imagery, for example, Kosslyn (1980) postulates twelve elementary mental operations such as picture, find, put, image, regenerate, look for, scan. For example, the scan function performs the operation of "moving all points in surface matrix along a vector; fills in new material at leading edge via an inverse mapping function." Each operation performs a specific cognitive

function.

When these mental operations are concatenated in a flow diagram, one has a computational model in the sense that it should allow a computer to perform the prescribed imagery task. Kosslyn uses as an example the task of examining whether an image of an automobile does or does not contain a spare tire.

In recent years some aspects of tasks such as reading (Rummelhart & McClelland, 1982) have been analyzed in terms of computational models. These models, show that the set of elementary operations proposed by the model are sufficient to produce the cognitive performance described. The top two levels of Figure 1 are at the level of cognitive science in that they deal with efforts to provide a sufficient basis for an electro-mechanical system to perform the type of cognition listed (e.g., chess playing or imagery). They do not necessarily tell us how a human mind, still less a human brain, performs these operations. Nonetheless, these computational models provide us with a way of analyzing cognition that shows very clearly that cognitive tasks may be viewed as consisting of elementary operations which are combined in complex programs to solve the overall task.

In order to convert the abstract elementary operations of cognitive science to an analysis of human mental processes it is necessary to examine the components of these operations. Many such operations have been examined by chronometric experiments (Posner, 1978). These chronometric experiments require human subjects to perform elementary operations such

as "scanning a list", "matching items", "zooming", postulated by the cognitive models. Such experimental studies have shown evidence of time locked component facilitations and inhibitions that occur in the process of performing these elementary operations. For example, suppose a person is required to scan a list of digits to determine if a single probe digit is a member of a previously presented list (Sternberg, 1966). The underlying processes could be examined by measuring the reaction time to respond "yes" or "no" as a function of number of items in the list. This analysis allows a detailed exmination of a mental operator similar to one posited by many computer programs that require comparing a target with items stored in a list. If a human being is required to perform this task it takes approximately 30 milisec per digit as the length of the list is increased from 1 to 6 digits.

The time locking of this putative comparison operation is impressive. Moreover, we know that the activation of any item during the comparison process produces a facilitation in processing items that are similar to it (Posner, 1978). For example, as the subject thinks about the digit 3 he potentiates the efficiency (e.g., speeds reaction time or reduces threshold) with which that visual digit is handled. In addition, we also know that when one attends actively to a digit, there will be an inhibition in the processing of items not sharing that pathway (Neely, 1977). Thus, the elementary operation involved in comparing the probe digit with items in store may be studied in terms of time locked facilitations and inhibitions that affect

probed responses. Some mental operations, including matching, naming, rotations, zooming, have been studied in terms of component facilitations and inhibitions. The results provide a psychological or information processing account of the underlying mental events involved in the task. These operations take place in real time and at a much slower rate than would of the case for existing computer sytems.

Some psychologists and philosophers have stressed the sufficiency of this kind of component analysis in providing a basis for information processing models of cognition. They argue it is unneccessary to go further and ask to what extent are neural systems related to such components. However, other psychologists, including most readers of this journal, do wish to go further.

Indeed there is reasonable evidence that components of the event related potential are systematically related to such component operations. For example, in 1978 I reviewed evidence that the time for release of the P-300 was related to the degree of priming or activation of an underlying psychological pathway. Evidence since then (Duncan-Johnson & Donchin, 1982) has shown that the latency and amplitude of the P-300 is systematically related to the benefits obtained in priming a pathway by a pre-cue. There is a good deal of independence between the degree of P-300 change and changes in reaction times with cuing, suggesting that the P-300 indexes somewhat different mental processes than are indexed by reaction time.

Naatanen (1982) has shown that systematic negative shifts in

the event related potential can be associated with the direction of the subject's attention. For example, if subjects are attending to the right ear, stimuli on that ear will show a negative shift with respect to stimuli occurring on an unattended channel (e.g. left ear) that takes place approximately 100 millisec after input. Naatanen argues that the latency of these negative shifts depend upon the extent of processing prior to reaching a level at which attention is directed. If attention is directed to a more complicated aspect of stimuli, e.g., frequency, the negative shift will occur later than if it is directed toward ear of entry. Harter and Guido (1980) have shown systematic negative shifts occurring about 200 msec for visual stimuli that match the spatial frequency to which the subject's attention has been directed. Since we know that attending to a particular pathway will activate that pathway (McLean & Shulman, 1978) it seems reasonable to suppose that the processing negativity discussed by Naatanen is, in fact, a brain sign related to the facilitation obtained in chronometric experiments.

This assumption has a number of remaining difficulties. Most of the performance priming experiments use a trial by trial design. The prime is introduced at the start of the trial and a subsequent target on that trial is shown to be affected by the prime. However, most of the work reviewed by Naatanen requires successive presentation of a number of stimuli and indeed, the negative shift is reduced or lost when there is a long time between successive inputs. Most of the chronometric

experiments seem to indicate that facilitation can occur either automatically from the presentation of the stimulus itself or from an act of attention. Naatanen suggests, altho gh his experiments do not prove, that attention is the necessary condition for the negative shifts found in the EEG.

The very suggestive work from the EEG can now be supplemented by other methods of relating component facilitations and inhibitions to brain systems. These other methods include magnetic potentials,, study of blood flow, and the study of the effects of brain lesions. For example, Knight, Hillyard, Woods & Neville (1980) have shown that lesions in the parietal lobe will affect the degree of processing negativity obtained when subjects are instructed to attend to one ear rather than the other.

In the case of attention to visual locations there are also data available from single cell recording that do appear to converge upon our effort to relate component facilitations to underlying brain systems. During the last fifteen years neurophysiologists have been able to record from single cells in alert monkeys doing cognitive tasks. Summaries of this work (Wurtz, Goldberg & Robinson, 1980) indicate that single cells in the posterior parietal lobe of alert monkeys show a phenomenon called selective enhancement. Such cells show enhanced rates of firing when a target occurs in their receptive field and attention is directed toward that receptive field as compared to conditions when a target occurs in their receptive field and

attention is directed elsewhere. Selective enhancement to shifts of covert attention (unaccompanied by eye movements) does not occur in other areas of the brain such as frontal eye field, striate cortex, or superior colliculus. The convergence of evidence from processing negativity studies using EEG recording and from the single cell results suggests that an understanding of the component processes involved in orienting attention to positions in space may be a particularly good one for testing the overall framework outlined in Figure 1.

Covert Orienting

One cognitive operation that we have in common with other animals is the ability to shift attention from position to position in the visual field. This activity is cognitive in the sense that it requires an alert organism in active contact with its environment. Moreover, this operation of shifting attention is a very important component of a number of cognitive models. For example, Kosslyn's (1980) scan mechanism allows a shift of attention spatially from one part of the visual image to another. Similarly, models of the visual system (Feldman, 1982; Treisman & Gelade, 1980) postulate an ability to bring attention to any location thus making available mental apparatus allowing more complex computations that can be performed in parallel across the visual field. This is often done by overt movements of the head and eyes which align the fovea with the area of the visual field of interest. However, in recent years it has been shown that it is possible to direct visual attention to a location within the

visual field without any overt orientation of head and eyes (Posner, 1980) Such covert orienting of attention can be measured by changes in efficiency, particularly in the latency and threshold for detecting events that occur at the location to which attention has been directed in comparison to other locations of similar eccentricity in the visual field.

My colleagues and I (Posner, 1980; Posner & Cohen, 1984; Posner, Cohen & Rafal, 1982; Posner, Walker & Friedrich & Rafal, in press) have studied a very simple task which embodies many of the features of covert orienting. In this task, the subject's eyes are fixated at a central location on a cathode ray tube. At the beginning of each trial, a cue is presented by brightening a square located 7 degrees to the left or right of fixation. The cue remains present for 150 msec. Following the onset of the cue, a target stimulus is presented either at the cued location or on the opposite side of the CRT. The results of a typical experiment of this type is shown in Figure 2. The X axis indicates the time

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between onset of the cue and the target. Plotted on the Y axis is the reaction time to respond to a target. The top two lines (square symbols) are from the first day in which the target was equally likely to occur on the cued or uncued side. Since this is the first day, subjects are a bit slower than on the second day. The results show clearly the rapid advantage in reaction time for the cued side (solid squares) over the uncued side (open squares) that begins about 50 after the cue and remains

present over the entire interval except at the last point where there is a slight crossover. Subjects are systematically faster on the cued side than on the uncued side. The circles show conditions when the cued side has a probability .8 of getting a target. Under these conditions, the subjects are also faster on the cued side (solid circles) than the uncued side (open circles) and remain so throughout the interval. Even when the cue signifies that the target is unlikely (.2) to occur on the cued side (triangles) there is a temporary facilitation on the side of the cued (solid triangles) that is replaced after 300 millisec by an advantage to the side which has the higher probability of the target (uncued side, open triangles).

What do these results indicate? First, the advantage of the cued side over the uncued side arises because the subject's attention is drawn toward the cue. There is evidence in the literature supporting this explanation, since similar advantages are found when the cue is a central arrow, which indicates the side likely to get the target stimulus (Jonides, 1981; Posner, 1980). There does not need to be any peripheral energy change to obtain this result, although such an energy change is an efficient way of summoning the subject's attention. Figure 2 also illustrates this point because when the probability is .8 that the detection stimulus will occur on the uncued side, after 300 millisec subjects show a strong advantage in reaction time to targets on the uncued side. Indeed, there is also evidence that suggests that the reaction time advantages which we show for cued targets are also accompanied by a reduction in the threshold for

detecting such targets (Bashinski & Bachrach, 1980). The use of central cues or probability differences show that the facilitation involves a mechanism that can either be pulled by a cue at the target location or directed from a cue that merely provides information about the target location.

A second point is the impressive time locking of the change in efficiency to presentation of cues. Time locking is very important if we are going to relate these results to neural systems. Within 500 millisec we see first an advantage on the cued side and then an advantage toward the high probability side whether cued or not.

The change in attention that occurs in covert orienting can be seen to involve three more elementary mental operations. These are shown in Figure 3. They include disengagement from

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Insert Figure 3 about here

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the current focus of attention which may in this task be at fixation, movement across the visual field from the current location of attention to the target and finally, engagement in the target. The time to disengage attention from a current focus is a function of the depth of processing at that focus (LaBerge, 1974). That is, subjects more heavily engaged in processing a stimulus at some target location will take longer to produce disengagement. There is evidence that attention movements are in some sense an analog operation. Kosslyn's model indicates that the scanning of a visual images is analog and his own data from experiments requiring subjects to access different locations in

an image shows a linear relationship between RT and the distance from the current location of attention to the target location. Tsal (1983) has shown similar linear relationships between the distance of a visual target from fixation and the time following a cue when one obtains maximum facilitation at the target location. His data indicate that attention moves at the rate of about 8 millisec per degree. This figure fits quite well with the data shown in Figure 2 in which a target about 7 degrees from location shows facilitation by about 50 millisec following the cue. More direct evidence of an analog movement across the visual field has been obtained by Shulman, Remington & McLean (1979) who showed faciliation of probe events at intermediate locations between fixation and the target occurs at times intermediate between introduction of the cue and finding maximal facilitation at the target location.

Once attention reaches the target location, it seems reasonable to postulate that it will take more time to engage the target task depending upon the complexity of the information processing necessary to reach the level of the system corresponding to the task instructions given the subject.

A final characteristic of the demonstration experiment illustrated in Figure 2 is the tendency for the advantage of the cued side over the uncued side to dissappear over time. We (Posner & Cohen, 1984) believe that this is due to an inhibitory effect of the peripheral cue. This inhibition is seen most clearly if attention is summoned first to the periphery and then back to fixation. The previously cued location is now inhibited

in comparison to other locations. Thus, it is possible by using peripheral cues to study time locked facilitation followed by inhibition. Inhibition is striking in Figure 2 when one compares the dotted triangles with the solid circles at 500 millisec delay. Both these conditions represent locations at which a target will occur with .8 probability, but the latter is on the side that was formerly cued. Even though the cue has disappeared this side is slower than the comparable uncued condition.

Posner and Cohen (1984) have proposed a hypothesis concerning the functional significance of these time locked phasic changes in facilitation and inhibition. We argue that facilitation is achieved by the alignment of a central attentional system with the pathway indicated by the cued event. This view is implied by the finding that both central and peripheral cues produce facilitation. Inhibition depends more upon the sensory information presented in the cue since there is no inhibition following the central cue.

According to this functional hypotheses, facilitation and inhibition work together in the process of visual orienting in the following way. When the eyes are fixed, a peripheral visual stimulus tends to summon attention rapidly to its location. Attention marks this area and gives priority to information there. Thus, cued locations are processed faster. Under some conditions a movement of the eyes will follow in the direction of the facilitated area. As the eyes move, attention is reoriented back to the fovea. It is not necessary for an eye movement to induce attentional orienting to the fovea since there are

conditions in which facilitation moves in retinotopic coordinates (Posner & Cohen, 1984). However, in most situations the fovea is favored because objects of interest tend to be foveated and also because it serves to keep attention and the fovea coordinated during successive changes of eye position. When one reorients away from the target by an eye movement, the previously facilitated target location is inhibited so there is a bias against returning the eyes to the previously cued environmental location. While inhibition occurs with and without eye movements (Posner & Cohen, 1984) it appears closely related in a functional sense to the eye movement system. Thus, the inhibition effect would serve as one of many neural systems designed to favor novelty over repetition. In accord with this hypothesis, it has been found that inhibited positions are less likely to draw the eyes back to them (Posner, Choate & Vaughan, in preparation; Vaughan, 1984).

While this hypothesis remains speculative, it does suggest that there are functional advantages for the component facilitations and inhibitions that have been found in experiments on spatial orienting. Thus they tend to link the component facilitations and inhibition to important ecological factors in the subject's visual environment.

Neural Systems

I hope the foregoing indicates that the study of covert orienting has provided a reasonably simple but rich functional model of an internal cognitive operation. Moreover, the ability to describe the operations of covert orienting in terms of time

locked component facilitations and inhibition suggests that it can be related to underlying neural systems as well. For a hundred years in clinical neurology it is known that lesions, particularly of the right parietal lobe produced problems that can be described, at least in part, as a difficulty in orienting attention to the side of space contralateral to the lesion (see DeRenzi, 1982 for a review). These results from clinical neurology of course fit with the material that we have mentioned from EEG studies showing a reduction in the N 100 when patients with parietal lesions had their attention directed to one ear (Naatanan, 1982) and for single cell recording results suggestion that cells in the posterior parietal lobe show selective enhancement (Wurtz, et al, 1980).

We have been studying such patients using experiments like those illustrated in Figure 2 (Posner, Cohen & Rafal, 1982; Posner, Walker, Friedrich & Rafal, in press). Figure 4 shows the data of one typical parietal patient. Recently we have summarized similar data from thirteen such patients (Posner, et al, in press). This particular patient, R.S. had a

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right parietal tumor which was excised, removing most of the right parietal lobe. In this study, 80% of the targets were on the cued side. The target remained present for only one second and we waited five seconds for a response. The patient serves as his own control because we contrast responses to targets on the contralateral side which go directly to the lesioned hemisphere,

with targets ipsilateral to the lesion which go directly to the intact hemisphere. We reasoned that if parietal lesions interfere with covert orienting of attention, we ought to find great difficulty in the subject orienting to targets opposite the lesion.

For trials where the target is on the cued side (solid lines) this patient showed a small but consistent advantage to targets ipsilateral to the lesion over those appearing contralateral to the lesion. In fact, some of the parietal subjects that we have run show no advantage on cued trials between the two sides. The time between the cue and the target did not affect this relationship strongly, suggesting that the results were not mediated by eye movements and also suggesting that the effect of the cue was similar irrespective of the side on which the cue occurred.

We can next examine the relation between ipsilateral targets on the cued and uncued sides. These are shown by the triangles. There is a clear cuing effect that emerges by 550 millisec after the cue. This is a relatively slow cueing effect compared with our normal subjects. However, the advantage for the cued side is of a size that approximates normal. We have found parietal patients who show both rapid and slow cuing effects.

The results are strikingly different when targets are presented on the side contralateral to the damaged hemisphere. If attention is drawn to the good side by a cue (open circles) there is massive inteference with the processing efficiency of

the target. At short intervals this effect is so great in subject R.S. that the patient usually does not detect the target within the five seconds allowed. This represents a confirmation of findings in clinical neurology where on double stimulation the subject is unable to report information contralateral to the lesion. However, even with intervals of 1000 millisec so that the cue is gone from the field there is massive interference with reaction time.

In further work (Posner et al, in press) we have found the same massive interference when we brighten the central box thus drawing attention to the fixation location. The central cue provides no information on target location and yet it produces a massive interference with reaction time. This suggests subjects have difficulty with the mental operation which we call disengage. That is, they seem to be able to move their attention normally once it is disengaged but they have difficulty in disengaging to any event that occurs in a direction contralateral to the lesion.

Our results with parietal patients contrast rather strongly with lesions of the mid-brain obtained from patients suffering from progressive supranuclear palsy (Posner, Cohen & Rafal, 1982). These patients show a progressive loss in the ability to move their eyes in vertical directions while often maintaining for some period of time the ability to move their eyes in the horizontal direction. If we compare covert orienting to targets in a vertical direction with those obtained with targets in a horizontal direction we find that while subjects are able to

orient covertly in either direction when targets occur in a vertical direction the orientation is slowed. This slowing of orienting on both cued and uncued trials suggests that lesions of the mid-brain areas produce inteference not with the disengage but with the move operation.

Conclusions

I believe that the studies of covert orienting using chronometric paradigms with normal and brain injured subjects, event related potential methods, and single cell recording provide considerable evidence in support of the viewpoint outlined in our general framework. While the framework is rather general in orientation it does suggest some differences from views commonly asserted concerning the relationship between cognition and brain processes.

First, some psychologists (eg Neisser, 1976) have rejected the study of elementary mental operations by chronometric techniques because they do not seem neither ecologically valid nor linked to the underlying biology. It seems to me that the general framework outlined in Figure 2 provides deep and detailed links between these experimental studies and the underlying biology of neural systems.

Second, other critics have suggested that the event related potentials provide no meaningful links to the level of analysis at which individual neural cells perform information processing operations. However, the degree of convergence between EEG methods and single cell methods within our model spatial task seem to suggest that both are giving meaningful measures

of underlying mental operations in the paradigms that we have studied.

Third, there is no apriori way to ensure that the elementary mental operations postulated by computational models at the cognitive science level have a relationship to the mental activities that people perform. However, chronometric studies showing rather beautiful time locked relationships between component facilitations and inhiitions and these mental operations seem to suggest that in fact such theories often do postulate mental operations that are natural for human subjects to perform and provide meaningful analysis in terms of underlying components.

Thus the evidence seems to provide significant links between each level outlined in the general framework. Such links are particularly useful in being able to provide the family of a patient suffering from a brain insult with information concerning cognitive deficits that are most likely to result. We are a long way from having a theory sufficiently deep to do this but it appears that the kinds of links that we have been able to achieve do provide the possibility for more detailed clinical application.

In this paper I have attempted to provide something of an overview of modern cognitive science in relationship to the question of how cognitive processes are instantiated in neural systems. It is clear that this is a complex and largely unanswered question. However, I hope that I have provided some guide to the growing literature that suggests a possibility that

detailed theories linking cognitive processes to neural systems and indeed to single cell activity will become available in future years.

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Figure Captions

Fig. 1: A general framework for the linking of cognitive tasks to underlying neural systems. The top two rows represent active areas of cognitive science (dividing complex tasks into elementary operations), the third row indicates experimental psychology of the type described in this paper. The bottom rows deal with underlying neural populations and single cell activity.

Fig 2: Results of an experiment on covert orienting with 12 normal subjects. The solid figures (triangles, circles, squares) are for trials with targets on the cued side; the open figures on the uncued side. The dot-dash lines are results from day one where targets are equally likely to occur on the cued and uncued side. After day 1 six subjects were run in a condition where the targets occurred on the cued side .8 of the time and uncued .2 (solid lines). The other six were run in a condition where the targets occurred on the cued side .2 and the uncued side .8 (dash lines). After Posner, Cohen & Rafal, 1982. (see text).

Fig. 3: Three putative elementary operations involved in covert orienting task.

Fig. 4: Results of one illustrative right parietal patient in the covert orienting task. The basic results for target in the right visual field (triangles) resemble normals, in the left visual field (circles), however, there is a profound disruption with the efficiency of orienting to

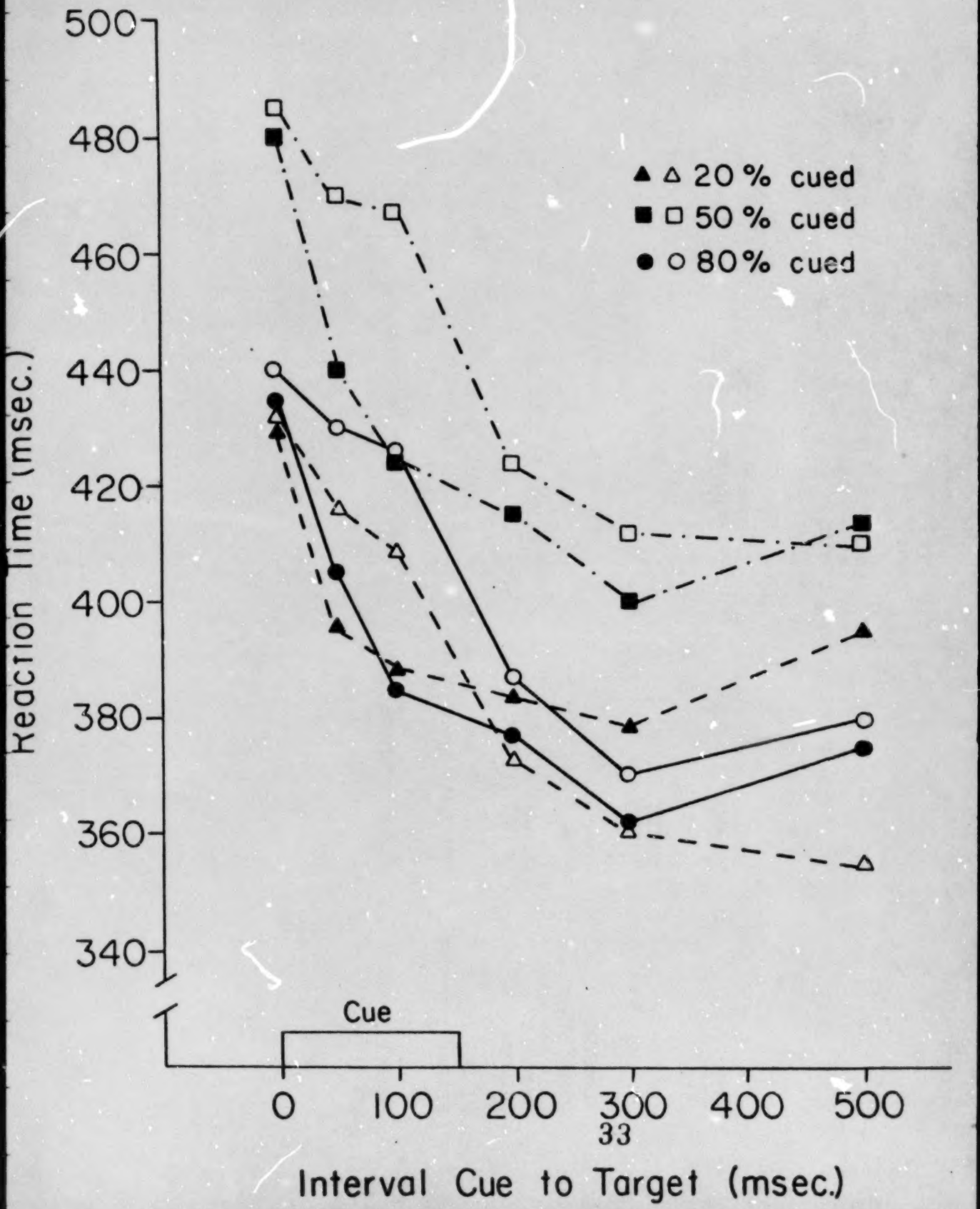
an uncued target. Cued targets are indicated by solid lines and uncued by dash lines. After Posner, Cohen, Rafal, 1982. (see text).

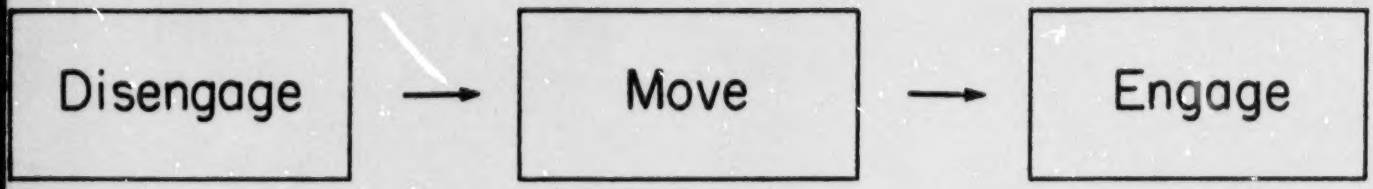
1. This paper was delivered as an invited address to the EPIC VII meeting in Florence, Italy, September, 1983. The theoretical framework was developed under ONR Contract No. N0014-83-K-1601 to the University of Oregon.

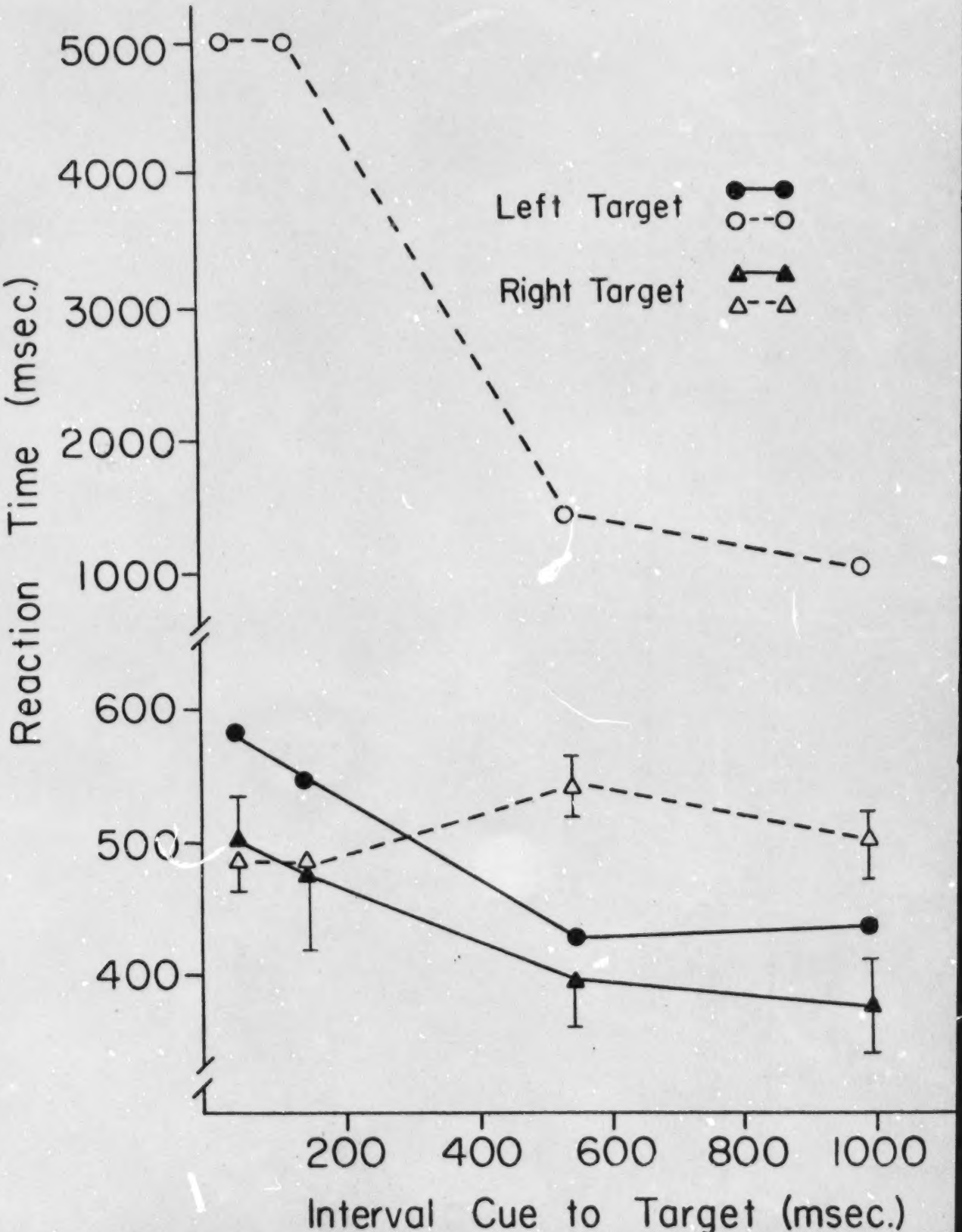
COGNITION AND NEURAL SYSTEMS

LEVEL	GENERAL EXAMPLES	COVERT ORIENTING TASK EXAMPLES
TASK	READING, SPEAKING IMAGERY	COVERT ORIENTING
ELEMENTARY OPERATIONS	NEXT, SCAN, NAME, ZOOM	DISENGAGE, MOVE, ENGAGE
COMPONENT ANALYSIS	FACILITATE PATHWAY INHIBIT PATHWAY	FACILITATE LOCATION
NEURAL SYSTEMS	PROCESSING NEGATIVITY P300	MIDBRAIN (SUPERIOR COLLICULUS) PARIETAL LOBE
CELLULAR ACTIVITY	SELECTIVE ENHANCEMENT	LIGHT SENSITIVE CELLS

Figure 1


500
480
460
440
420
400
380
360
340
Reaction Time (msec.)
▲ △ 20 % cued
■ □ 50 % cued
● ○ 80 % cued
Cue
0
100
200
300
400
500
Interval Cue to Target (msec.)


Disengage
Move
Engage


5000
4000
3000
2000
1000
600
500
400
Reaction Time (msec.)
Left Target
Right Target
200
400
600
800
1000
Interval Cue to Target (msec.)

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